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AN APPROACH TO THE MEASUREMENT OF THE POTENTIAL STRUCTURAL DAMAGE OF EARTHQUAKE GROUND MOTIONS

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SUMMARY

The quantification and prediction of damage due to different seismic actions to structure types of different strength is an important problem not yet solved in the Earthquake Engineering field. In addition, owing to the fact that macroseismic information cannot be used directly in dynamic calculations, a new problem appears when these are the only kind of data available. Thus, there is a need to estimate a parameter to relate the energy of the ground motion and the damage occurrence, and eventually achieve a better seismic risk assessment. After the study and review of some representative potential damage parameters, attention has been paid to the Arias intensity (unfiltered and filtered in certain frequency ranges) and the Cumulative Absolute velocity (CAV) as the parameters to evaluate the energy of movement, and to relate them with the observed damage. The data used to infer these correlations have been provided by the ENEA-ENEL (Italy). The information consists of strong motion records from the Campano Lucano (1980), Umbria (1984) and Lazio-Abruzzo (1984) earthquakes, and data of damage to buildings in the vicinity of recording instruments (within a maximum radius of 300 m, where the soil conditions remain constant). In this paper, some relations have been obtained to quantify the damage level for different seismic inputs. The results suggest that unfiltered Arias intensity and CAV (for calculation threshold 20 cm/s^2) correlate well with the macroseismic information used. Best fits are obtained between the quoted parameters and the observed damage in type A structures.

KEY WORDS: Arias intensity; cumulative absolute velocity; potential damage; vulnerability

INTRODUCTION

The objectives of this work arise from two main sources of problems involved in seismic risk research. The first one concerns the poor reliability achieved in prediction and quantification of damage to different kinds of structures, due to varying seismic actions. The second refers to the need for the estimation of parameters that enable the energy of ground motion to be related to the damage occurrence. In this way it would be possible to convert the macroseismic information into suitable values for design. These problems are already well known and many engineering ground motion parameters aimed at evaluating the severity or destructiveness of earthquakes have been proposed in the literature.[1–19] After a general overview of this subject, in a preliminary analysis, we tested several relationships between representative parameters of ground motion energy and damage data. We observed that two of these parameters, Arias intensity and CAV, show good correlation with macroseismic information. Given the fact that these parameters take into account the

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amplitudes and the duration of the movement, they seem to provide a suitable means to reflect the energy of the ground motion. For these reasons, we focused our attention on examining their behaviour as damage potential parameters.

GENERAL OVERVIEW

The peak ground acceleration was the more extensively used parameter to measure the destructiveness although it did not prove very reliable. The first instrumental intensities defined by Benioff[1] and later by Housner[2] are obtained from the integration of the displacement response spectrum and velocity response spectrum, respectively. Later on, Blume,[3] defined an instrumental intensity as a collection of nine selected spectral ordinates of the velocity response spectrum. Arias[4,5] defined an instrumental intensity considering the three orthogonal components of the ground motion's acceleration and giving it a tensorial character. From the Arias intensity, Arroyo and Espinosa[6] regarded the intensity as a function of frequency maintaining the tensorial character. However, few of these parameters have been correlated with the damage observed in places where earthquake ground motions were recorded and in other cases the correlation was low. Saragoni[7] and Araya and Saragoni[8] have shown that the Arias intensity predicts the destructiveness capacity in a suitable way only when the frequency content of different earthquakes is similar. They have introduced a certain normalization of Arias intensity, defined as destructiveness potential factor which can be expressed as a function of the duration, maximum ground acceleration and frequency content of the strong ground motion. In the branch of earthquake-resistant analysis and design, some authors have proposed parameters to measure the damage potential taking into account different models of performance of the structures. Park *et al.*[9] propose a characteristic intensity related to hysteretic energy, maximum displacement and ultimate displacement under monotonic loading. Uang and Bertero[10] and Bertero,[11] after analysing several engineering parameters (peak ground acceleration and velocity, Housner spectral intensity, Arias intensity, Araya and Saragoni destructive potential factor, etc.), have concluded that considering ground motion records alone or with the parameters derived from the response of an elastic system is not sufficient for assessing the damage potential given the fact that damage implies inelastic deformation. They propose the earthquake energy input for a SDOF system with linear elastic perfectly plastic behaviour for different ductility and damping ratios, as the damage potential parameter. Tso *et al.*[12] characterize the energy content of the ground motion records using the peak acceleration-to-velocity ratio. This parameter is related to the energy demands in MDOF systems. Rodríguez[13] has shown the lack of consistency between the damages observed in buildings in Mexico City and some parameters like the characteristic intensity[9] and the energy input.[10] He proposes a measure of seismic damage capacity that involves response parameters such as a non-dimensional hysteretic energy, an acceptable roof drift ratio and the maximum drift ratio for an SDOF equivalent system. An alternative methodology tries to establish dependences and relationships between ground motion features and vulnerability observed in structures. In this case, the study of the destructiveness capacity of different seismic inputs takes into account the effects on structures through some classifications of these and of the damages. Following this line several works have succeeded to assess the energy of motion which can affect a structure in a more reliable way. For instance, Arias intensity and cumulative absolute velocity are correlated with damage by EPRI[14] to obtain the best damage potential parameter that is able to give a damage threshold for nuclear facilities. Spence *et al.*[15,16] and Coburn and Spence[17] have proposed a scale to measure damage of ground motion, called PSI scale (parameterless seismic intensity), derived directly from damage data and addressed to the vulnerability estimation. This scale has been correlated with various ground motion parameters, and provides acceptable correlation for peak horizontal ground acceleration and for mean response spectral acceleration. Liu and Zhang[18] have found that, statistically, the peak velocity in the first place and the peak acceleration in the second, turn out to be a suitable destructiveness index, while the duration was of second-order in comparison with these. Benito[19] has shown that parameters consisting of products of amplitude and duration seem to give good results for destructiveness estimation. The present paper is also focussed on the study of correlations between two macroseismic parameters — local intensity and observed damage — and two instrumental parameters obtained from strong motion records — Arias intensity (filtered and unfiltered) and standard cumulative absolute velocity. An attempt has been made to

test these parameters and to improve the assessment of the ground motion destructiveness. The measurement of these parameters is described in the next section.

PARAMETER DESCRIPTION

Given the importance of the aforementioned parameters in the present study we review their definitions as well as the main aspects.

Arias intensity

The Arias intensity[3,4] (AI) is a measure of the damage capacity based on the ground motion energy (by weight unit) dissipated by a population of structures (SDOF systems) uniformly distributed in frequencies. It is expressed as

$$I_{ij} = \frac{\pi}{2g} \int_{t_0}^{t_0 + D} a_i(t) a_j(t)\, \mathrm{d}t \tag{1}$$

where D is the duration of the record and $a_i(t)$, $a_j(t)$, are the acceleration amplitudes of the orthogonal components i, j, respectively. This parameter has a tensorial character (nine components), although in practical applications, the scalar values I_{xx}—intensity in one direction— and $I_h = I_{xx} + I_{yy}$ —horizontal intensity— are more often used. Thus, the Arias intensity characterizes the energy content of a strong motion record. In order to take into account different distributions of structures in frequency, the accelerogram can be filtered in different bands, thus obtaining for each a computed value referred to as the filtered Arias intensity ($\mathrm{AI_F}$).

Cumulative absolute velocity

The CAV is defined as the area under the absolute accelerogram:

$$\mathrm{CAV} = \int_{t_0}^{t_0 + D} |a(t)|\, \mathrm{d}t \tag{2}$$

It can be seen as the sum of the consecutive peak-to-valley distances in the velocity time history. Another interpretation of the CAV is as the area under the acceleration versus duration curve. In this way the CAV regards the contribution of both the amplitude and the duration of motion. This parameter was originally proposed by Kennedy and Reed in a study sponsored by the Electrical Power Research Inst. (EPRI),[14] as the second optional exceedance criterion of the OBE (Operating Basis Earthquake), in nuclear power plants. The study concluded that the OBE is considered to have been exceeded if both of the following conditions are satisfied: the 5 per cent damped ground response spectrum for the earthquake motion at the site at frequencies between 2 and 10 Hz exceeds the corresponding OBE design response spectrum, and the computed CAV value from the earthquake record is greater than 0·30 g s. The CAV value of 0·30 g s was determined, in the above-mentioned study, from the database used and it defines the threshold of damage for nuclear power plants. Later on, the method of calculating CAV was modified to remove the dependence on records of long duration containing low (non-damaging) accelerations.[20] The new adjusted threshold of potential damage for CAV, in nuclear power plants, was found to be 0·16 g s. The method to standardize the CAV calculation consists in calculating incrementally the parameter in 1 s intervals as follows:

$$\mathrm{CAV} = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} |a(t)|\, \mathrm{d}t \tag{3}$$

where $a(t)$ are acceleration values in a 1 s window, where at least one value exceeds a predetermined level of acceleration (typically 0·025 g) and $i = 1, 2, \ldots, n$; n being the record length in seconds. Thus, the standard cumulative absolute velocity, CAV, becomes a discrete sum of integrals calculated in 1-s windows. Each window contributes to the sum only if it has at least one peak that exceeds the fixed level of acceleration. In this way the extended lull zones of the accelerogram containing low and non-damaging amplitudes are filtered.

EARTHQUAKE DATA DESCRIPTION

In this study, macroseismic and instrumental information provided by the ENEA-ENEL (Italy) have been used. These data correspond to the Italian earthquakes which occurred in Campano-Lucano (23 November 1980); Umbria (29 April 1984); Lazio-Abruzzo (7 May 1984) and Lazio-Abruzzo (11 May 1984). The

Table I. MSK scale criteria

Types of structures (*Buildings not anti-seismic*)

(A) Buildings in field-stone, rural structures, adobe houses, clay houses
(B) Ordinary brick buildings, buildings of large block and prefabricated type, half timbered structures, buildings in natural stone
(C) Precast concrete skeleton construction, precast large panel construction well built wooden structures.

Damage levels

0. No damage
1. Slight damage: Fine cracks in plaster, fall of small pieces of plaster
2. Moderate damage: Small cracks in walls, fall of fairly large pieces of plaster, cracks in chimneys, parts of chimneys fall down
3. Heavy damage: Large and deep cracks in walls; fall of chimneys
4. Destruction: Gaps in walls; part of buildings may collapse, separate parts of the building lose their cohesion, inner walls and filled in walls of the frame collapse
5. Total damage: Total collapse of buildings

Table II. Data used (ENEA-ENEL)

Earthquake	Station	Ep. dist. (km)	Soil cond.	Loc. int. (MSK)	Max. acc. (cm/s^2)	Max. vel. (cm/s)
C. Lucano 23/11/80	Arienzo	77·4	0	6	34·4	3·5
	Roccamonfina	127·8	2	6	32·3	6·0
	Bagnoli Irp.	22·3	0	7	163·7	37·0
	Brienza	41·3	1	6·5	202·4	10·5
	Mercato S. Seve.	47·9	2	6·5	141·8	10·5
	Sturno	34·8	0	7·5	306·6	70·0
	Calitri	17·8	2	7·5	177·2	27·3
	Auletta	22·9		6	59·8	7·8
	Rionero In Vult.	34·8	2	7	99·1	15·3
	Bisaccia	28·1	0	6	98·5	22·6
	Benevento	60·6	2	6	57·8	9·5
	Tricarico	71·8	2	5·5	42·1	6·5
	Bovino	53·8	2	5	49·3	3·7
Umbria 29/04/84	Peglio	48·2	1	5	51·6	2·3
	Citta Di Castello	32·9	2	5	46·7	3·6
	Nocera Umbra	30·6	0	6	189	5·8
	Umbertide	17·5	0	6	36·5	1·4
	Pietralunga	18·7	0	6	177·1	9·0
Lazio Ab. 07/05/84	Atina	15·4	0	7	104·1	4·7
	Isernia S. Agapito	45	2	6	70·2	3·3
	Pontecorvo	33·9	2	5	83·7	4·3
	Manoppello	58·5		6	137	9·3
	Orttuchio	32·7	2	5	83·1	4·2
	Lama Dei Peligni	82·7		6	81·5	5·0
Lazio Ab. 11/05/84	Villetta Barrea	5·8	0	6	231·7	9·6

respective magnitudes M_L were 6·5, 5·0, 5·1 and 4·7, and the respective MCS epicentral intensities I_0 were IX–X, VII–VIII, VII–VIII, and VII (see Reference 22). The 25 three-component accelerations were recorded by the Italian strong motion network of the ENEA-ENEL in different site conditions, defined by the parameter $S = 0, 1, 2$ (rock, shallow alluvial, and depth alluvial, respectively), and have epicentral distances ranging from 6 to 128 km. The macroseismic information consists of the local intensity of each station, evaluated by Margottini *et al.*,[21,22] and the damage data to more than 100 buildings from the vicinity of recording instruments (within a maximum radius of 300 m, where the geological conditions remain constant). The analysed buildings and the damage data have been classified following the MSK scale (1981) criteria summarized in Table I. The used data are shown in Tables II and III.

Table III. Damage data (ENEA-ENEL). Each number under the column 'Damage grades' corresponds to one single observation

Station (*N* observations)	Damage grades			Station (*N* observations)	Damage grades		
	Type A	Type B	Type C		Type A	Type B	Type C
Arienzo (4)		2	1	Nocera Umbra (7)	3	0	
		2	2			0	
Roccamonfina (2)		0				1	
		1				2	
Bagnoli Irp. (5)	3	0				2	
	3	3				2	
	3			Umbertide (3)	2	0	
Brienza (5)	2		1		2		
	3		1	Pietralunga (5)	2	2	
	3					2	
Mercato S. Se. (6)	3	0	0			2	
	4	0	0			2	
Sturno (4)	3	3		Atina (2)	3		
		3			3		
		3		Isernia S. Agap. (9)	2	0	0
Calitri (5)	3	4			2	0	0
	3					0	
	4					0	
	4					1	
Auletta (4)	1	1		Pontecorvo (4)		0	
	2	2				0	
Rionero (5)	3	1	2			0	
	3	2				0	
Bisaccia (0)				Manopello (12)	3	0	0
					3	0	0
Benevento (2)			2			0	0
			3			1	0
Tricarico (6)	1	0				2	1
	1	0		Orttuchio (5)		0	0
		0				0	
		0				0	
Bovino (4)			0			0	
			0	Lama Dei Pel. (6)	2	2	
			1		3	2	
			1			2	
Peglio (3)	0		0			2	
	0			Vill. Barrea (5)	0		0
Citta Di Cast. (5)	1		0		1		
	2		0		2		
			0		3		

PARAMETER CALCULATION

The Arias intensity (AI) and the standard cumulative absolute velocity (CAV) for five different acceleration thresholds, were calculated for all the records. In most of the records analyzed it was observed that the maximum values of AI and CAV corresponded to the horizontal components of greater peak acceleration, with few exceptions, just where the two horizontal components were very close. Therefore, from each station, the records corresponding to horizontal components of greater peak acceleration were selected. The Fourier amplitude spectrum was calculated for each of the 25 components, in order to examine the spectral composition of the ground motions. As a sample of quality of the records, Figure 1 shows the Fourier amplitude spectrum of some of the components used.

AI_F calculation

The selected records were filtered in the frequency domain, by means of Ormsby band-pass filters, using three different bands between 0·2 and 10 Hz. The cut-off and roll-off frequencies of the band-pass filters used were B1(0·2, 0·9–7·8, 8·5) Hz, B2(0·3, 0·8–5·5, 6·0) Hz, and B3(2·0, 2·5–7·0, 7·5) Hz. Thus, the filtered Arias intensity (AI_F) was calculated for each component and each frequency band.

CAV calculation

The five acceleration levels taken to calculate the CAV were 25, 20, 15, 10 and 5 cm/s^2. In each case, this implies neglecting the contribution of the sum of those 1-s windows that do not have a value larger than these levels. It is important to note the role that this calculation threshold plays in the estimation of the parameters. In fact, obtaining the suitable threshold was one of the partial goals of this work.

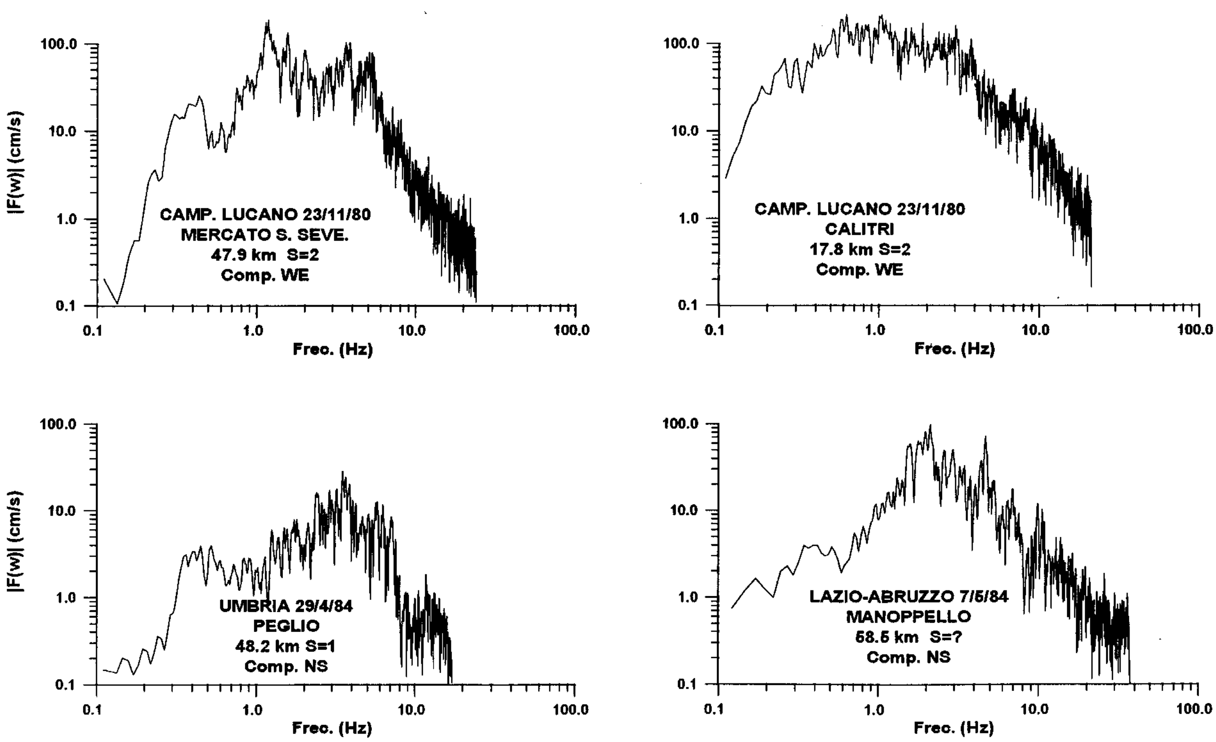

Figure 1. Examples of Fourier spectra (horizontal component of greater peak acceleration) used in this work

CORRELATION AND OBTAINED RESULTS

The obtained results for different filtered bands of Arias intensity and calculation thresholds of CAV are explained below. For the AI we have compared the relations obtained by using filtered and unfiltered data. For the CAV the comparisons were made by introducing different threshold values.

Relationships with local intensity

Graphic correlations of the two parameters studied, AI and CAV, with macroseismic intensity were first analyzed. The results are shown in Figures 2–5. Figure 2 shows the obtained values for AI and AI_F in the frequency bands (B_1, B_3) as a function of local intensity. The results for the band B_2 are quite similar to those given by the other bands, and hence not presented. Strong dispersion for the intensity degree VI can be noted. This fact may indicate a certain ambiguity of the MSK scale in the definition of this degree, as already observed by many authors.[23–25] Moreover, when the three plots are compared, it may be noticed that the

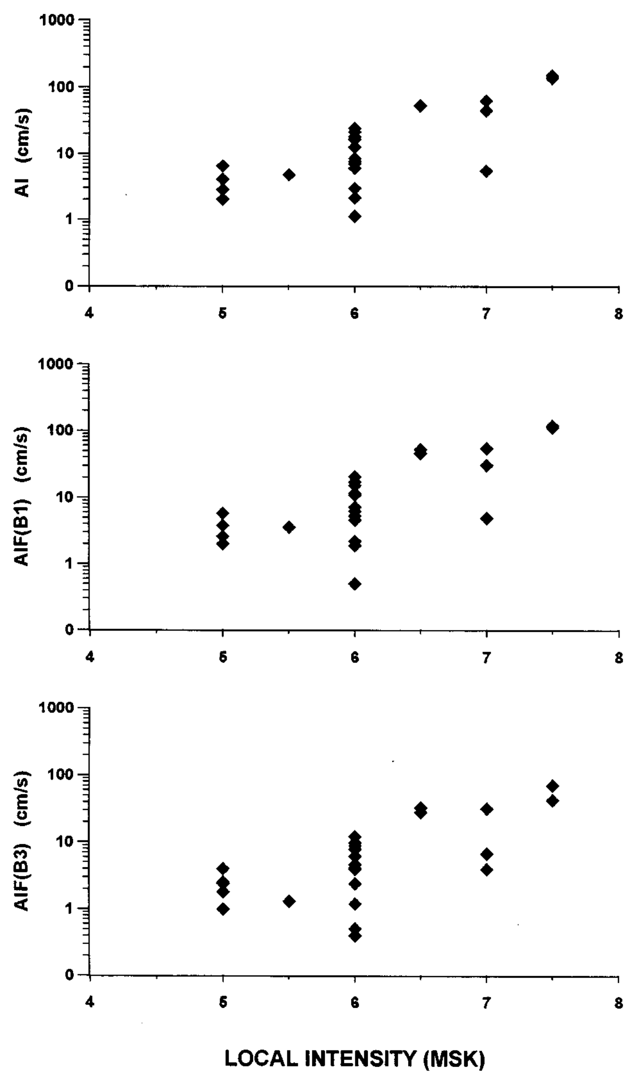

Figure 2. Arias intensity (unfiltered and filtered bands B1, B3) versus local intensity

introduction of the filters does not improve the fit. This result does not confirm our initial expectation that better adjustments could be reached by eliminating extreme values of frequency. In any case it is necessary to consider the absence of information about the natural periods of the analyzed structures. Thus, the selection of frequency bands of the filters becomes uncertain. Therefore, the utility of the filters cannot be completely discarded. A precise estimation of the natural periods of the buildings would be highly recommended in order to improve this kind of studies. The plots show an exponential trend in the behaviour of AI and AI_F when the local intensity increases. Choosing the unfiltered Arias intensity as the best result, mean values for each degree of local intensity are presented in Figure 3, as well as the regression line obtained by the least-squares fit. By this the exponential trend is confirmed, and a good fit is obtained. The corresponding analytical expression is

$$\log(\mathrm{AI}) = 1{\cdot}50 I_L - 6{\cdot}42, \quad R^2 = 0{\cdot}92 \tag{4}$$

where log is the natural logarithm and R^2 the coefficient of determination of the fit.

A similar analysis was conducted with the standard CAV for different acceleration thresholds or levels. Figure 4 shows this parameter as a function of local intensity for the acceleration levels 25, 20 and 15 cm/s^2. The same exponential trend is also observed in the behaviour of this parameter, as well as a strong dispersion of values for intensity VI. In addition, if the results related to the three acceleration thresholds are compared, the best correlation is found for the second value, i.e. for 20 cm/s^2. The mean values of CAV for each intensity degree, corresponding to the calculation threshold 20 cm/s^2 as well as the regression line are presented in Figure 5. The quality of this fit is similar to that obtained with AI. Its analytical expression is

$$\log(\mathrm{CAV}) = 1{\cdot}24 I_L - 3{\cdot}54, \qquad R^2 = 0{\cdot}91 \tag{5}$$

Correlation with observed damage

An analysis similar to the previous one was carried out with the observed damage in the three types of structures: A, B and C. Figures 6 and 7 show the correlation of the two parameters studied with the level of damage. The values represented as more significant after the previous analysis, correspond to the AI and the CAV for the threshold acceleration value of 20 cm/s^2. The behaviour of these two parameters is quite similar; therefore, it may be explained jointly. For type A structures, AI and CAV show a well-defined exponential trend as a function of the level of damage, with strong dispersion of values related to damage grade 2, the same as observed with local intensity VI. In type B structures, a large dispersion of values is found for levels of damage 0, 1 and 2, where the majority of observations are included. This fact implies that structures may

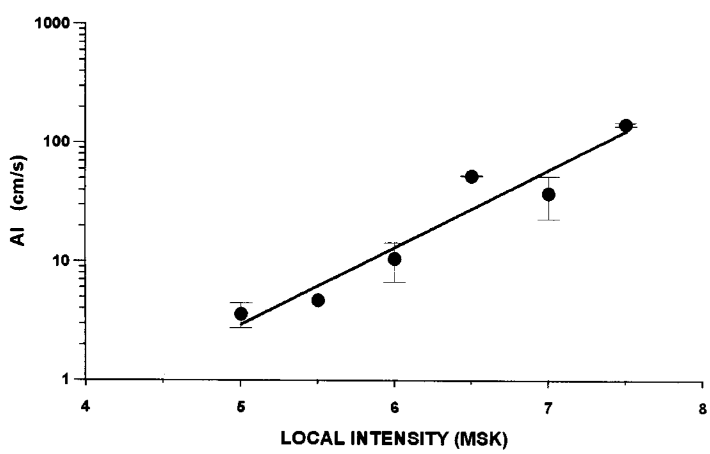

Figure 3. Arias intensity versus local intensity

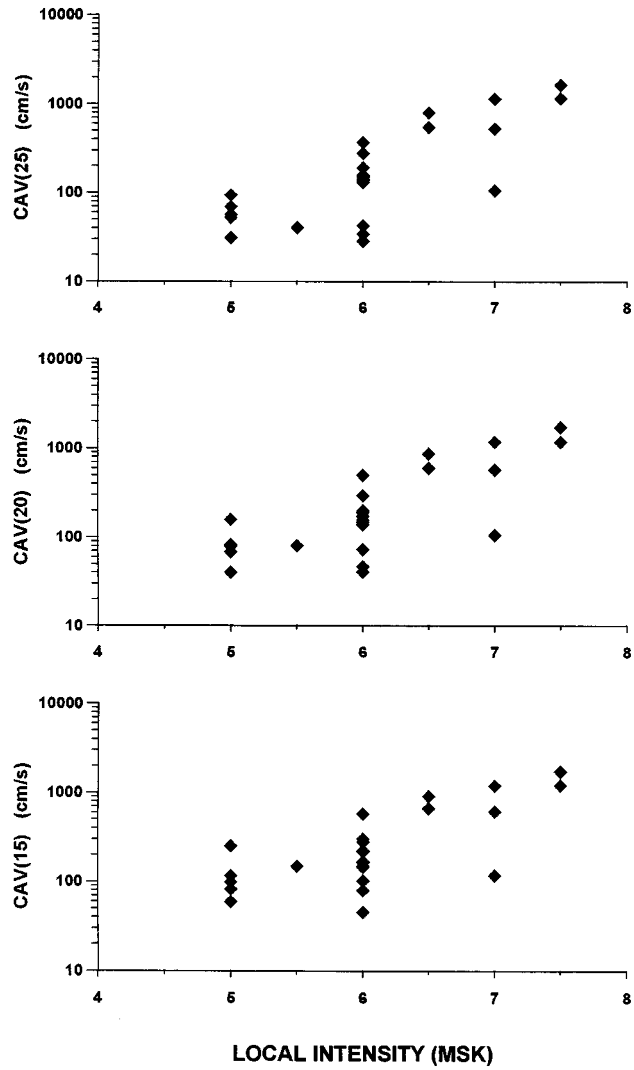

Figure 4. Cumulative absolute velocity (calculation threshold 25, 20 and 15 cm/s^2) versus local intensity

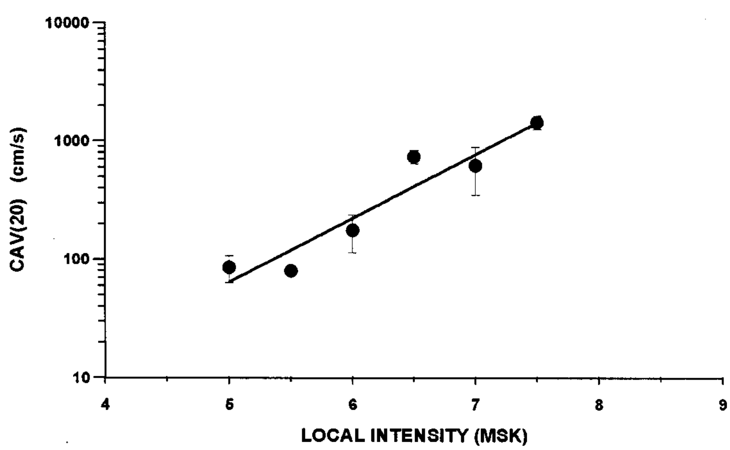

Figure 5. Cumulative absolute velocity (calculation threshold 20 cm/s^2) versus local intensity

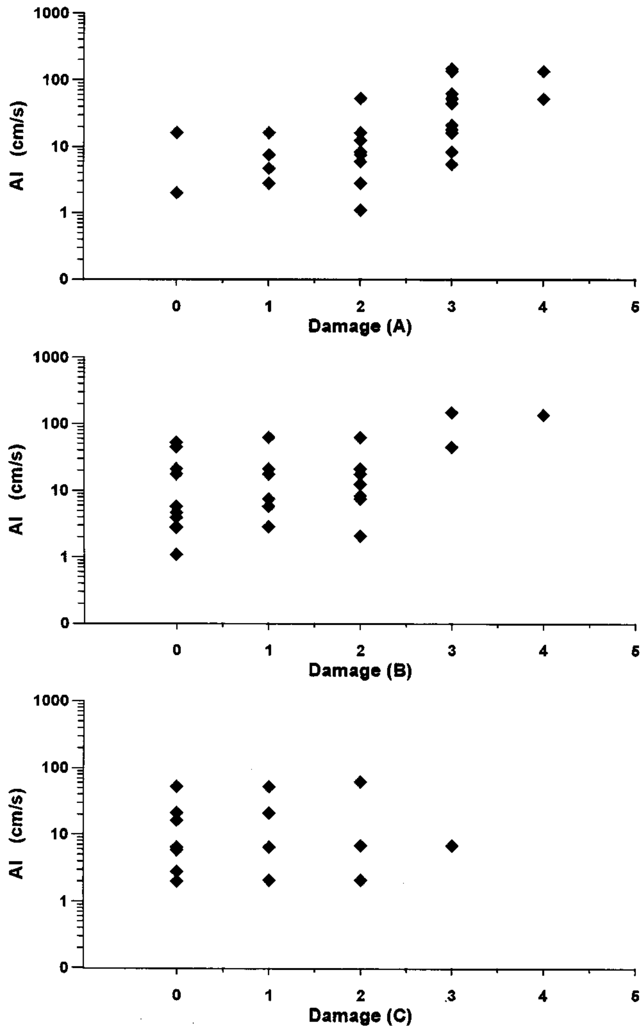

Figure 6. Arias intensity versus damage grades (structure types A, B, C)

respond without damage, or be slightly or moderately damaged under movements characterized by a wide range of values of AI and CAV(20). Comparing graphs corresponding to structures A and B, it is possible to see that observations corresponding to type B are located in the lower damage levels. This proves that this kind of structure suffers lesser damage than those of type A, under equal level of movement. For structures of type C an anomalous behaviour is found. The absence of damage data greater than 3 does not allow the establishment of a clear trend in this case. It is only evident that this kind of structure responds in a different way compared to those of type A or B. Besides, the A type structures are the only ones which show an exponential fit between parameters of movement and damage level. Figure 8 contains the representation of the fits corresponding to mean values of AI and CAV (20) for each damage grade. Good correlations are obtained, defined by the following expressions:

$$\log(\mathrm{AI}) = 0{\cdot}75D_{\mathrm{A}} + 1{\cdot}49, \qquad R^2 = 0{\cdot}90 \tag{6}$$

$$\log(\mathrm{CAV}(20)) = 0{\cdot}75D_{\mathrm{A}} + 4{\cdot}10, \qquad R^2 = 0{\cdot}94 \tag{7}$$

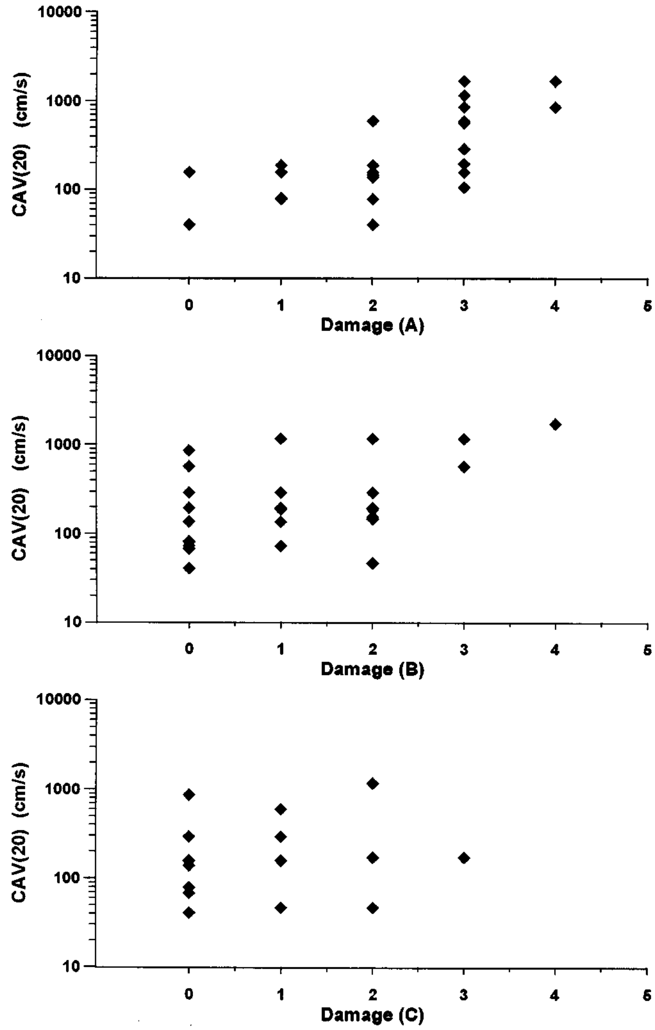

Figure 7. Cumulative absolute velocity (calculation threshold 20 cm/s^2) versus damage grades (structure types A, B, C)

These laws constitute a partial result of the work, which may allow us to translate instrumental information to damage data for this kind of building.

CONCLUDING REMARKS

The present work aimed to supply empirical estimations of vulnerability. According to the classification of the EAEE WG3 (Reference 26) the *input* data are collected damage information, qualitative characteristics of buildings, and seismic characterization of sites; the *method* uses statistical analysis; and the *output* can be considered as the absolute vulnerability. Therefore, vulnerability is characterized through relationships among parameters which represent strong motion energy and parameters representative of the damage suffered by the structures.

The sample of observations available is neither too extensive nor homogeneous. Thus, being conscious of this limitation, the results may be considered orientative, allowing the establishment of behaviour trends of

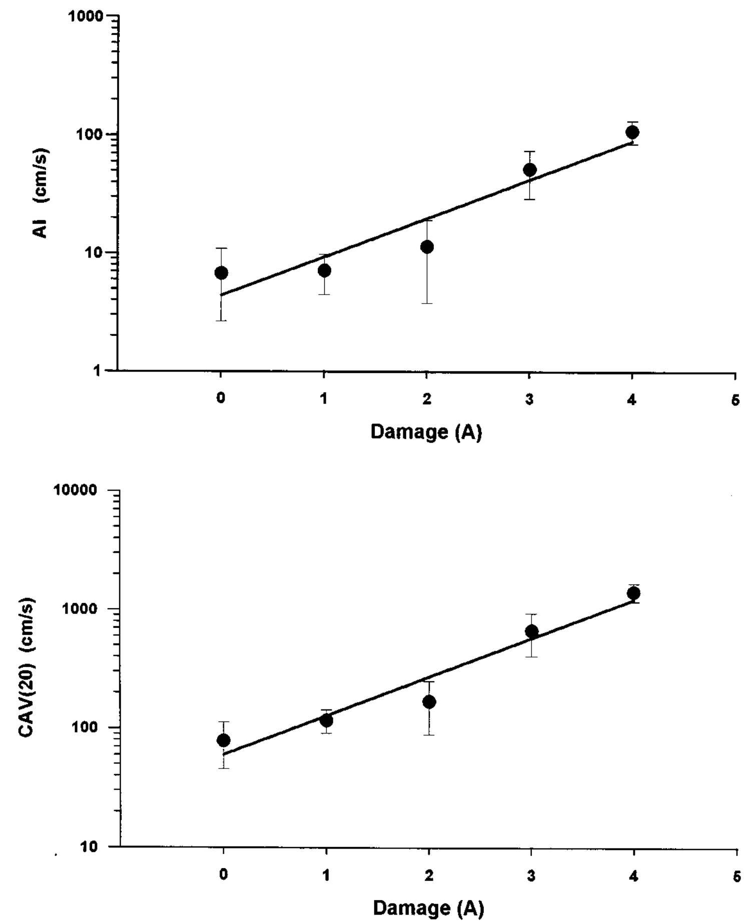

Figure 8. Arias intensity and cumulative absolute velocity (calculation threshold 20 cm/s^2) versus damage grades (structure type A)

the studied parameters, Arias intensity and cumulative absolute velocity, in relation with the damage occurrence. The study does not claim to reach conclusive relationships. These might be obtained from more complete data sets with a similar treatment to that proposed here.

The accomplished study allows us to infer some conclusions, which may be summarized in the following points:

1. The two analysed parameters of ground motion AI and CAV, display an exponential trend as a function of local intensity. This fact implies that the energy of movement, calibrated through both parameters, grows exponentially as the local intensity increases by one degree. The best correlations have been obtained for the unfiltered AI and for the threshold acceleration of 20 cm/s^2 related to CAV. The mean values of these parameters display the fits given by the expressions

$$\log(\mathrm{AI}) = 1{\cdot}50 I_{\mathrm{L}} - 6{\cdot}42, \qquad R^2 = 0{\cdot}92 \tag{4}$$

$$\log(\mathrm{CAV}(20)) = 1{\cdot}24 I_{\mathrm{L}} - 3{\cdot}54, \qquad R^2 = 0{\cdot}91 \tag{5}$$

where the local intensity, I_{L}, ranges between 5 and 7·5 in the MSK scale.

2. In the correlation of both parameters with the damage, a clear exponential trend for type A buildings is observed too. Good fits are found for the unfiltered AI and CAV for the acceleration level already mentioned.

The estimated relationships are the following:

$$\log(\mathrm{AI}) = 0{\cdot}75 D_{\mathrm{A}} + 1{\cdot}49, \qquad R^2 = 0{\cdot}90 \tag{6}$$

$$\log(\mathrm{CAV}(20)) = 0{\cdot}75 D_{\mathrm{A}} + 4{\cdot}10, \qquad R^2 = 0{\cdot}94 \tag{7}$$

D_{A} being the damage level for type A structures.

3. Type B structures show strong dispersion of AI and CAV values in the damage grades ranging from 0 to 2.

4. For type C structures it is difficult to establish a clear trend, due to the absence of damage data greater than 3. This is, in fact, an evidence of the different behaviour of these structures with regard to the previous one, and the need for independent analysis in seismic risk studies.

5. It would be convenient to classify buildings according to their natural period and then filter the Arias intensity in the frequency band similar to this period. In this way an improvement of the correlation is expected.

6. Finally, the study may be extended to other parameters which represent ground motion energy capable of damaging the structures. These parameters would not be an alternative to the complete spectrum of movement; rather, they can contribute as a complementary criterion to estimate the damage capacity of ground motion.

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